# DIGITAL SINE/COSINE WAVE GENERATOR

by

**Tony Chun-Hung Huang**

**Hai Thanh Ho**

Merchant & Gould P.C.
P.O. Box 2903
Minneapolis, MN 55402-0903

# DIGITAL SINE/COSINE WAVE GENERATOR

## Related Applications

This application claims priority of United States provisional application Serial Number 60/236,315 filed September 28, 2000.

## Field of the Invention

This application relates generally to sine/cosine wave generation and more particularly to a microprocessor implemented digital sine/cosine wave generator.

## Background of the Invention

Sine and cosine wave generators are currently used in number of different applications. For example, sine and cosine wave generators are typically used in communications systems to provide a sine or cosine carrier wave to modulate or demodulate a signal. Sine/cosine generators are also frequently used in system analysis to generate sine and/or cosine waves which are injected into a system to determining the AC characteristics of the system. For example, sine/cosine wave generators are typically employed in a disc drive system to determine the open and closed loop responses of the disc drive servo system. Sine/cosine wave generators may be implemented in either analog or digital circuits. Additionally, sine/cosine generators may be implemented by discrete circuits or by microprocessors.

Discrete analog sine/cosine generators may involve using logarithmic op-amps or other non-linear forms of signal integration to produce a sine or cosine wave. While these circuits are generally inexpensive, sine waves generated in this manner generally have a noticeable amount of distortion. Discrete digital sine/cosine generators may use digital to analog converters to generate a sign wave. For example, sine/cosine wave generators using multiplexers or counters (and sometimes both) are well known. Typically, these types of sine/cosine generators of are unsuitable in smaller applications where reduced circuit size and low cost is desirable or necessary.

A number of programmable sine/cosine wave generators have been devised. Typically, systems of this type generate a number discrete points in digital form by a microprocessor or an array processor. These points are then converted to an analog sine/cosine wave by a digital-to-analog converter circuit. The programming for this type of sine/cosine generator is

generally implemented in either software or micro-code. Because of the software based nature of such generators and the time required for the code to execute, the process often does not operate fast enough for real time applications. Consequently, those prior art systems often use a memory to store a pre-generated representation of a sine wave, and the data stored in the memory then is clocked out to a digital-to-analog converter at a prescribed rate. If a low distortion sine wave is desired then a substantial amount of non-volatile memory must be provided for storing enough data points (particularly at higher frequencies). As non-volatile memory may greatly increase the cost of a given system, these types of sine/cosine generators are unsuitable in smaller applications where reduced circuit size and low cost is desirable or necessary.

Accordingly there is a need for a non-table derived microprocessor implemented sine/cosine generator.

## Summary of the Invention

Against this backdrop the present invention has been developed. One aspect of the present invention relates to a digital sine/cosine generator having a sine/cosine wave generation module which employs a difference equation to generate either a digital sine wave or a digital cosine wave based on two initial conditions, one of which is received form a coefficient generation module. The difference equation employed by the sine/cosine wave generation module is preferably of the form $y(n) = b*y(n-2) - y(n-1)$. The coefficient generation module preferably generates a series of values representative of a sine wave and a series of values representative of a cosine wave.

Another aspect of the present invention relates to a computer-readable media having stored thereon a computer executable coefficient generation module that generates a series of values according to a function $B(N) = \sin(2\pi NFT)$ and a discrete periodic waveform generation module that receiving one of the series of values generated by the coefficient generation module to generate a discrete periodic waveform utilizing a difference equation.

Yet another aspect of the present invention relates to a method of generating a discrete periodic waveform using a discrete difference equation. The method involves selecting a first value representative of a first initial condition of the difference equation and generating a second value representative of a second initial condition of the difference equation. Based on these initial conditions a sequence of values representative of a periodic waveform are

generated using the discrete difference equation and the first and second values as initial conditions.

These and various other features as well as advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

## Brief Description of the Drawings

FIG. **1** is a plan view of a disc drive incorporating a preferred embodiment of the present invention showing the primary internal components of the disc drive.

FIG. **2** is a simplified functional block diagram of the disc drive shown in FIG. **1**.

FIG. **3** is a simplified functional block diagram of a servo control loop of the disc drive shown in FIG. **1**.

FIG. **4** depicts a digital sine/cosine wave generator in accordance with the present invention.

FIG. **5** depicts an embodiment of a sine/cosine generation module of the digital sine/cosine wave generator shown in FIG. **4**.

FIG. **6** depicts a flowchart for operations of the sine/cosine generation module shown in FIG. **5**.

FIG. **7** depicts a coefficient generation module of the digital sine/cosine wave generator shown in FIG. **4**.

FIG. **8** depicts a flowchart for operations of the coefficient generation module shown in FIG. **5**.

FIG. **9** depicts a graph of various data points generated by the coefficient generation module and the sine/cosine generation module shown in FIG. **4**.

FIG. **10** depicts a flowchart for operations of the digital sine/cosine wave generator shown in FIG. **4**.

## Detailed Description

In general, the present disclosure describes methods and systems for generating values representative of a sine wave and/or a cosign wave. More particularly, the present disclosure describes a unique microprocessor implemented digital sine/cosine wave generator. More particularly still, the present disclosure describes a microprocessor implemented digital sine/cosign wave generator which utilizes a coefficient generator module to provide starting

parameters or coefficients for a sine/cosine wave generator module, such that sine waves and/or cosine waves of different frequencies can be generated. The present disclosure also describes a disc drive system having a digital sine/cosine wave generator operable for injecting a sine wave and/or a cosign wave into a servo loop of a disc drive system such that a frequency response of the servo loop may be determined.

The following is description of an exemplary operating environment embodiment for the present invention. In particular, reference is made to practicing the digital sine/cosine wave generator of the present invention with respect to a processor in a disc drive system such as disc drive **100**, as shown in FIG. **1**. In such a system the digital sine/cosine wave generator of the present invention may be used to inject a series of sine waves and/or cosine waves into a servo control loop, such as servo loop **300** (FIG. **3**), of a disc drive, such as disc drive **100**, in order to determine the frequency response of the servo loop. While the digital sine/cosine wave generator of the present invention is described herein with respect to its application in a disc drive, it is to be understood that the digital sine/cosine wave generator of the present invention is not limited to its use in a disc drive environment or to its use in determining system frequency responses. In this respect, the digital sine/cosine wave generator of the present invention may be used in a number of other environments, such as other computing environments and non-disc drive related environments without departing from the scope of the present invention.

A disc drive **100** incorporating a preferred embodiment of the digital sine/cosine wave generator of present invention is shown in FIG. **1**. The disc drive **100** includes a base **102** to which various components of the disc drive **100** are mounted. A top cover **104**, shown partially cut away, cooperates with the base **102** to form an internal, sealed environment for the disc drive in a conventional manner. The components include a spindle motor **106** which rotates one or more discs **108** at a constant high speed. Information is written to and read from tracks on the discs **108** through the use of an actuator assembly **110**, which rotates during a seek operation about a bearing shaft assembly **112** positioned adjacent the discs **108**. The actuator assembly **110** includes a plurality of actuator arms **114** which extend towards the discs **108**, with one or more flexures **116** extending from each of the actuator arms **114**. Mounted at the distal end of each of the flexures **116** is a head **118** which includes an air bearing slider

enabling the head **118** to fly in close proximity above the corresponding surface of the associated disc **108**.

During a seek operation, the track position of the heads **118** is controlled through the use of a voice coil motor (VCM) **124**, which typically includes a coil **126** attached to the actuator assembly **110**, as well as one or more permanent magnets **128** which establish a magnetic field in which the coil **126** is immersed. The controlled application of current to the coil **126** causes magnetic interaction between the permanent magnets **128** and the coil **126** so that the coil **126** moves in accordance with the well known Lorentz relationship. As the coil **126** moves, the actuator assembly **110** pivots about the bearing shaft assembly **112**, and the heads **118** are caused to move across the surfaces of the discs **108**.

A flex assembly **130** provides the requisite electrical connection paths for the actuator assembly **110** while allowing pivotal movement of the actuator assembly **110** during operation. The flex assembly includes a printed circuit board **132** to which head wires (not shown) are connected; the head wires being routed along the actuator arms **114** and the flexures **116** to the heads **118**. The printed circuit board **132** typically includes circuitry for controlling the write currents applied to the heads **118** during a write operation and a preamplifier for amplifying read signals generated by the heads **118** during a read operation. The flex assembly terminates at a flex bracket **134** for communication through the base deck **102** to a disc drive printed circuit board (not shown) mounted to the bottom side of the disc drive **100**.

Referring now to FIG. **2**, shown therein is a functional block diagram of the disc drive **100** of FIG. **1**, generally showing the main functional circuits which are typically resident on a disc drive printed circuit board and which are used to control the operation of the disc drive **100**. As shown in FIG. **2**, the host computer **200** is operably connected **206** to an interface application specific integrated circuit (interface) **202** via control lines, data lines, and interrupt lines. The interface **202** typically includes an associated buffer **210** which facilitates high speed data transfer between the host computer **200** and the disc drive **100**. Data to be written to the disc drive **100** are passed from the host computer to the interface **202** and then to a read/write channel **212**, which encodes and serializes the data and provides the requisite write current signals to the heads **118**. To retrieve data that has been previously stored by the disc drive **100**, read signals are generated by the heads **118** and provided to the read/write channel **212**, which performs decoding and error detection and correction operations and outputs the

retrieved data to the interface **202** for subsequent transfer to the host computer **100**. Such operations of the disc drive **200** are well known in the art and are discussed, for example, in U.S. Pat. No. 5,276,662 issued Jan. 4, 1994 to Shaver et al.

As also shown in FIG. **2**, a microprocessor **216** is operably connected **220** to the interface **202** via control lines, data lines, and interrupt lines. The microprocessor **216** provides top level communication and control for the disc drive **200** in conjunction with programming for the microprocessor **216** which is typically stored in a non-volatile microprocessor memory (MEM) **224**. The MEM **224** can include random access memory (RAM), read only memory (ROM) and other sources of resident memory for the microprocessor **216**. Additionally, the microprocessor **216** provides control signals for spindle control **226**, and servo control **228**.

As shown in FIG. **3**, the micro-processor **216**, the servo control **228**, the head **118**, and the read/write channel form what is commonly referred to as the servo loop **300** of the disc drive **100**. In operation of the disc drive **100**, as the head **118** travels over a track **302** on the disc **108**, the head reads analog servo information present on the track **302**. This servo information, which is indicative of the location of the track **302** on the disc **108**, is then amplified and decoded by the read/write channel **212**. The read/write channel **212** typically includes an analog to digital converter (ADC) so that selected digital representations of the servo information are provided to the microprocessor **216**. The microprocessor **216** generates a position error signal (PES) from the servo information and uses the PES to generate and output a correction signal to a servo control **228**. The microprocessor **216** then determines correction signals in accordance with commands and programming steps, which are typically stored in the FLASH/ROM **224**. The correction signal is provided to the servo control **228**, which includes a power amplifier (not shown) that outputs a controlled dc current of a selected magnitude and polarity to the coil **126** in response to the correction signal. Thus, during track following mode, the servo information indicates the relative position error of the head **118** with respect to the center of the track **302** and the correction signal causes a correction in the dc current applied to the coil **126** in order to compensate for this position error and move the head **118** to the center of the track **140** (or another position relative to the track **302**, as desired). For additional discussion concerning the general construction and operation of servo loops, such as servo loop **300**, U.S. Pat. No. 5,262,907 entitled HARD DISC DRIVE WITH

IMPROVED SERVO SYSTEM, issued Nov. 16, 1993 to Duffy et al., assigned to the assignee of the present invention and incorporated herein by reference, as well as U.S. Pat. No. 5,136,439 entitled SERVO POSITION DEMODULATION SYSTEM, issued Aug. 4, 1992 to Weispfenning et al., assigned to the assignee of the present invention and incorporated herein by reference.

Preferably, the logical operations of the various embodiments of the sine/cosine generator of the present invention are implemented as a sequence of computer implemented steps or program modules running on a microprocessor, such as microprocessor **216**. It will be understood to those skilled in the art that the sine/cosine generator of the present invention may also be implemented as interconnected machine logic circuits or circuit modules within a computing system. The implementation is a matter of choice dependent on the performance requirements of the computing system implementing the sine/cosine generator. Accordingly, the logical operations making up the embodiments of the sine/cosine generator of the present invention described herein are referred to variously as operations, structural devices, acts or modules. It will be recognized by one skilled in the art that these operations, structural devices, acts and modules may be implemented in software, in firmware, in special purpose digital logic, and any combination thereof without deviating from the spirit and scope of the present invention as recited within the claims attached hereto.

Preferably, the operation of the sine/cosine generator of the present invention, is controlled by operating code which is typically stored in some type of computer readable media. Typically, the microprocessor **216** retrieves the operating code from the computer readable media and executes the operating code when appropriate. Computer-readable media can be any available media that can be accessed by the microprocessor **216**. By way of example, and not limitation, computer-readable media might comprise computer storage media and communication media.

Computer storage media includes volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules or other data. Computer storage media includes, but is not limited to, RAM, ROM, EPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or

any other medium that can be used to store the desired information and that can be accessed by the computing system **200**.

Communication media typically embodies computer-readable instructions, data structures, program modules or other data in a modulated data signal such as a carrier wave or other transport mechanism and includes any information delivery media. The term "modulated data signal" means a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal. By way of example, and not limitation, communication media includes wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, RF, infrared, and other wireless media. Combinations of any of the above should also be included within the scope of computer-readable media. Computer-readable media may also be referred to as computer program product.

As shown in FIG. **4**, an embodiment a digital sine/cosine wave generator **400** of the present invention comprises a coefficient generation module **410** and a sine/cosine generation module **412**. In general terms, the sine/cosine generation module **410** is functional to produce a series of discrete numbers at its output **430** that are representative of values along either a sine wave or a cosine wave. The frequency of the discrete time sine and/or cosine wave generated by the sine/cosine wave generation module **410** is dependent on the values received at inputs **424**, **426**, and **428** to the sine/cosine wave generation module **410**. As described in greater detail below, the coefficient generation module **410** is functional to generate appropriate input values to the sine/cosine generation module **410** such that various discrete frequency of sine and/or cosine waves may be generated by the sine/cosine wave generation module **410**.

As shown in FIG. **4**, the coefficient generation module **410** receives as inputs the value of $\sin(2\pi f_0 T)$ **414** and the value of $\cos(2\pi f_0 T)$ **416**, where $f_0$ is a predetermined frequency and $T$ is a specified tolerable granularity (period between successive intervals - typically below $1/2*f_0$, or the Nyquist frequency of the system). The values $f_0$ and $T$ are preferably predetermined in accordance with the operating parameters of the digital sine/cosine wave generator **400** and stored in computer readable media, such as buffer **210**, memory **224**, or registers within the microprocessor **216**. In a manner described in greater detail below, the coefficient generation module **410** uses the values **414** and **416** to generate as an output two

values, $\sin(2\pi f_0 NT)$ **418** and $\cos(2\pi f_0 NT)$ **420**. The values **418** and **420** are preferably stored in computer readable media, such as buffer **210**, memory **224**, or registers within the microprocessor **216**. Selector **422** selects either value **418** or **420** for input **424** into the sine/cosine generation module **412**, as variable $y(1)$.

In addition to variable $y(1)$, the sine/cosine generation module **412** also receives as one input **426** a constant $b$ and as another input **428** variable $y(0)$. In a manner described in greater detail below, the sine/cosine wave generation module **412** uses the values of the constant $b$, the variable $y(1)$, and the variable $y(0)$ to generate a series of discrete numbers as an output **430** $y(\mathrm{n})$ that is representative of values along either a sine wave or a cosine wave. The variable $y(1)$, the constant $b$, and the variable $y(0)$ are all preferably stored in computer readable media, such as buffer **210**, memory **224**, or registers within the microprocessor **216**. Whether the output **430** $y(\mathrm{n})$ will include the values of a sine wave or a cosine wave is dependent on the value **418** or **420** selected by selector **422** and delivered to input **424** of the sine/cosine generation module **412** as variable $y(1)$. For example, if the value $\sin(2\pi f_0 NT)$ **418** is input into the sine/cosine generation module **412** as variable $y(1)$ and a value of zero is input into the sine/cosine generation module **412** as variable $y(0)$, the values generated by the sine/cosine generation module **412** output as $y(\mathrm{n})$ will be representative of a sine wave. Alternatively, if the value $\cos(2\pi f_0 NT)$ **420** is input into the sine/cosine generation module **412** as variable $y(1)$ and the value one is input as variable $y(0)$, the values generated by the sine/cosine generation module **412** and output as $y(\mathrm{n})$ will be representative of a cosine wave.

Turning now to FIG. **5**, in describing the operation of the digital sine/cosine wave generator **400** it is helpful to look first at the operation of the sine/cosine generation module **412**. As is known in the art, the z-transform is a basic tool for both the analysis and implementation of discrete-time systems. As such, the z-transform is useful in analyzing and implementing various routines in digital hardware, such as microprocessors or microprocessor based systems. As is also well known, a linear system's characteristics are completely specified by the system's impulse response, as governed by the mathematics of convolution. With this in mind we may state that the output to the following equation results in a sine wave having an amplitude $A$ and a frequency $f$ when the input to the equation is a unit impulse:

$$\frac{Y(z)}{U(z)} = A\frac{\sin(2\pi fT)z}{z^2 - 2\cos(2\pi fT)z + 1} \qquad (1)$$

Similarly, we may state that the output to the following equation results in a cosine wave having an amplitude $A$ and a frequency $f$ when the input to the equation is a unit impulse:

$$\frac{Y(z)}{U(z)} = A\frac{z(z-\cos(2\pi fT))}{z^2 - 2\cos(2\pi fT)z + 1} \qquad (2)$$

As the denominators for equation (1) and equation (2) are identical, both equation (1) and equation (2) may also be expressed by the following difference equation

$$y(n) = by(n-1) - y(n-2) \qquad (3)$$

where $b = 2\cos(2\pi fT)$ and the initial conditions of the difference equation (3) are $y(1) = \sin(2\pi NfT)$ and $y(0) = 0$ for the generation of a sine wave, and $y(1) = \cos(2\pi NfT)$ and $y(0) = 1$ for the generation of a cosine wave.

FIG. **5** illustrates a realization of difference equation (3). As shown in FIG. **5**, the sine/cosine generation module **412** includes a first delay element **510**, a second delay element **512**, a multiplier **514**, and a summer **516**. As described above, inputs to the sine/cosine generation module **412** include a predetermined value $y(0)$ **428** indicative of an initial value of the sine or cosine wave that is to be generated, a predetermined value $y(1)$ **424** indicative of a second value of the sine or cosine wave that is to be generated, and a constant value $b$ **426**. The constant $b$ **426** is preferably has a value of $2\cos(2\pi f_0 T)$, where $f_0$ is a predetermined frequency and $T$ is a specified tolerable granularity (period between successive intervals - typically below $1/2*f_0$, or the Nyquist frequency of the system).

The sine/cosine generation module **412** is preferably implemented as operating code on the microprocessor **216** of the disc drive **100**. The operating code of the sine/cosine generation module **412** is preferably stored in some type of computer readable media, such as microprocessor memory (MEM) **224**.

As shown in FIG. **5**, in operation of the sine/cosine generation module **412**, the initial values y(0) and y(1) are set to predetermined values, as described above depending on whether a sine wave or a cosine wave is desired at output $y$(n). As the operation of the sine/cosine generation module **412** proceeds the values of $y(0)$ **518** and $y(1)$ **520** will be replaced in accordance with the functioning of the sine/cosine generation module **412**, as described below. As shown in FIG. **5**, multiplier **514** multiplies the value y(1) **424** by the constant $b$ **426**. The output of the multiplier **514** is then fed to the positive input **526** of the summer **516**. Likewise,

the value of $y(0)$ **428** is fed to the negative input **528** of the summer **516**. As a result of the summing operation carried out by the summer **516**, the output of the summer **516** is then $y(n) = by(1) - y(0)$. As also shown in FIG. **5**, after a predetermined delay cause by delay **510**, the value of $y(1)$ is replaced by the value $y(n)=by(1)-y(0)$. Similarly, after a predetermined delay caused by delay **512**, the value of $y(0)$ is replaced by the initial value of $y(1)$, or $\sin(2\pi f_0 NT)$. The operation of the sine/cosine generation module **412** then continues on in a similar manner, with the value of $y(1)$ being multiplied **514** by the coefficient $b$ **426** and added **516** to the negative of the value of $y(0)$, and so on until the operation of the sine/cosine generation module **412** is halted.

The operational flow of the sine/cosine generation module **412**, and thus an implementation of the difference equation (3), may alternatively be shown with respect to the flow diagram of FIG. **6**. As shown in FIG. **6**, at the start **608** of the operational flow of the sine/cosine generation module **412**, initialization operation **610** initializes the values of $y(0)$, and $y(1)$ as described above, depending on whether a sine wave or a cosine wave is desired at output $y(n)$. As described in greater detail below, the initial values for $y(0)$ and $y(1)$ will be set by the coefficient generation module **410**.

Following the initialization of the of $y(0)$, $y(1)$, and $b$, calculate operation **612** calculates $y(n) = by(1) - y(0)$ using the values for $y(0)$, $y(1)$, and $b$ set by initialization operation **610**. Next, output operation **614** outputs the value of $y(n)$ as calculated by calculate operation **612**. Following output operation **614**, set operation **616** sets the $y(1)$ equal to the value of $y(n)$ previously calculated by calculate operation **612** and sets the $y(0)$ equal to the value of $y(1)$ as initialized at initialization operation **610**. Determination operation **618** then ascertains whether operation of the sine/cosine generation module **412** has been completed. The determination of whether operation of the sine/cosine generation module **412** has been completed is preferably based on user defined criteria, such as whether values corresponding to a full sweep, or a number of full sweeps, of a sine wave have been output by the output operation **614**. If the user defined criteria for the completion of the sine/cosine generation module **412** is met, operation of the sine/cosine generation module **412** is ended **620**. If the user defined criteria is not met, the operational flow of the sine/cosine generation module **412** is directed back to the calculate operation **612** and $y(n) = by(1) - y(0)$ is again calculated using the values for $y(0)$, $y(1)$, as set during the previous execution of set operation **616**, followed

by an output of the new value of $y$(n) by the output operation **614**. Following output operation **614**, set operation **616** sets the $y$(1) equal to the value of $y$(n) previously calculated by calculate operation **612** and sets the $y$(0) equal to the value of $y$(1) as set by the previous execution of the set operation **616**. The calculate operation **612**, the output operation **614**, the set operation **616**, and the determination operation **618** are continued in this manner until the user defined criteria for the completion of the sine/cosine generation module **412** have been met, at which time the operation of the sine/cosine generation module **412** is ended **620**.

Turning now to the operation of the coefficient generation module **410**. As shown in FIG. **7**, the coefficient generation module is in itself a sine/cosine generator. In operation the coefficient generation module **410**, as shown in FIG. **7**, employs the following well known trigonometric identities to generate sine waves and cosine waves:

$$\sin(a+b) = \sin(a)\cos(b) + \cos(a)\sin(b) \qquad (4)$$

$$\cos(a+b) = \cos(a)\cos(b) + \sin(a)\sin(b) \qquad (5)$$

As shown in FIG. **7**, the coefficient generation module **410** includes four multipliers **710**, **712**, **714**, and **716**, two summers **718**, **720**, and two delay units **722**, **724**. The coefficient generation module **410** receives as a first input $\sin(2\pi f_0 T)$ **726** and as a second input $\cos(2\pi f_0 T)$ **728**. Additionally, the coefficient generation module **410** is initialized with the values B(N) = $\sin(2\pi f_0 T)$ **732** and A(N) = $\cos(2\pi f_0 T)$ **730**. The input values **726** and **728** and the initialization values **732** and **730** are preferably stored in computer readable media, such as buffer **210**, memory **224**, or registers within the microprocessor **216**. As shown in FIG. **7**, the coefficient generation module **410** outputs both B(N)= $\sin(2\pi f_0 T)$ **734** and A(N)= $\cos(2\pi f_0 T)$ **736**. As such, the coefficient generation module **410** outputs both a series of discrete values indicative of a sine wave **734** and a series of discrete values indicative of a cosine wave **736**.

The operational flow of the coefficient generation module **410**, may alternatively be shown with respect to the flow diagram of FIG. **8**. As shown in FIG. **8**, at the start **810** of the coefficient generation module **410**, initialization operation **812** initializes: A = $\cos(2\pi f_0 T)$; B = $\sin(2\pi f_0 T)$; C = $\cos(2\pi f_0 T)$; and D = $\sin(2\pi f_0 T)$. The values of A, B, C, and D are preferably stored in computer readable media, such as buffer **210**, memory **224**, or registers within the microprocessor **216**. Next, calculate operation **814** calculates A(N) = A*D + B*C and B(N) = A*C - B*D and stores the results of these operations. The output operation **816** then outputs the values of A(N) and B(N) the outputs **736** and **734**, respectively, as shown in

FIG. 7. Determination operation **818** then determines if the next value has been requested. That is, a determination is made as to whether the next discrete value, or data point, along the sine or cosine waves being generated by the coefficient generation module **410** have been requested. If the next data point has been requested, set operation **820** sets A = A(N) and B = B(N), the operational flow of the coefficient generation module **410** is returned the calculate operation **814** and the operational flow of the coefficient generation module **410** continues on as shown in FIG. **8**. If, on the other hand, the next data point has not been requested, the operational flow of the coefficient generation module **410** is ended **822**. Inherent in the operation of the coefficient generation module **410**, is that during each iteration of the module **410**, that is, each pass through the operations **814**, **816**¸ **818**, and **820** the value of N is incremented, such that B(N) = $\sin(2\pi N f_0 T)$ and or A(N) = $\cos(2\pi N f_0 T)$, where N is the number of iterations of operations **814**, **816**¸ **818**, and **820**.

As described earlier, the coefficient generation module **410** provides appropriate input values to the sine/cosine generation module **412** such that the various frequency of discrete sine and/or cosine waves may be generated by the sine/cosine wave generation module **412**. Stated another way, the sine/cosine generation module **412** is operable to generate a series of discrete values which are representative of either a sine wave or a cosine wave. As shown in FIG. **4**, in order to generate these sine or cosine wave values, the sine/cosine generation module **412** must initially be provided two data points, or coefficients, along the discrete sine or cosine wave to be produced, as well as the constant $b$. The first data point $y(0)$ provided to the sine/cosine generation module **412** has a predefined value of either zero (0) if a sine wave is desired or one (1) if a cosine wave is desired. The second data point $y(1)$ provided to the sine/cosine generation module **412** is variable and determines the frequency of the discrete sine or cosine wave which is ultimately produced by the sine/cosine generation module **412**. As shown in FIG. **4**, the $y(1)$ variable is provided to the sine/cosine generation module **412** by the coefficient generation module **410**. That is, y(1) will either be A(n) or B(N), depending on whether values indicative of a sine wave or a cosine wave is desired at the output **430** of the sine/cosine generator **400**. The relationship between the value of A(N), for example, generated by the coefficient generation module **410** and the values of the sine wave or cosine wave generated by the sine/cosine generation module **412** can best be understood with reference to FIG. **9**.

The coefficient generation module **410** generates a series of equally spaced discrete data points. Each of these data points is generated in succession by the coefficient generation module **410** according to the equation $\sin(2\pi N f_0 T)$, where N is indicative of the relative position of the data point in the series of data points generated. In this sense, the data points generated by the coefficient generation module **410** represent sine and cosine waves in the frequency domain. For simplicity, only the first three data points **912**, **914**, and **916**, corresponding to N = 1, N = 2, and N =3, respectively are shown in FIG. **9**. Also shown in FIG. **9** are three additional sets of data points **920**, **922**, and **924**. The first **920** of the additional set of data points shown in FIG. **9** is representative of 1/2 of a sine wave, as generated by the sine/cosine generation module **412**. The second of the additional set of data points **922** shown in FIG. **9** is representative of a sine wave having a frequency exactly double the frequency of the sine wave **920** represented by the first additional set of data points, as generated by the sine/cosine generation module **412**. The third of the additional set of data points **924** shown in FIG. **9** is representative of a sine wave having a frequency exactly triple the frequency of the sine wave represented by the first additional set of data points **920**, as generated by the sine/cosine generation module **412**.

The set of additional data points **920** shown in FIG. **9** is illustrative of data points which have been generated by the sine/cosine generation module **412** in response to the value $B(N) = \sin(2\pi N f_0 T)$ being input to the sine/cosine generation module **412** as y(1) from the coefficient generation module **410**, where $N = 1$, and of the value of zero (0) being input to the sine/cosine generation module **412** as y(0). As will be apparent, the frequency of the sine wave **920** generated by the coefficient generation module **410** is identical to the frequency of the sine wave generated by the sine/cosine generation module **412**.

The set of additional data points **922** shown in FIG. **9** is illustrative of data points which have been generated by the sine/cosine generation module **412** in response to the value $B(N) = \sin(2\pi N f_0 T)$ being input to the sine/cosine generation module **412** as y(1) from the coefficient generation module **410**, where $N = 2$, and of the value of zero (0) being input to the sine/cosine generation module **412** as y(0). The frequency of the sine wave **922** generated by the coefficient generation module **410** is now to twice frequency of the sine wave generated by the sine/cosine generation module **412**.

Finally, the set of additional data points **924** shown in FIG. **9** is illustrative of data points which have been generated by the sine/cosine generation module **412** in response to the value B(N) = $\sin(2\pi N f_0 T)$ being input to the sine/cosine generation module **412** as y(1) from the coefficient generation module **410**, where $N = 3$, and of the value of zero (0) being input to the sine/cosine generation module **412** as y(0). The frequency of the sine wave **924** generated by the coefficient generation module **410** is now to twice frequency of the sine wave generated by the sine/cosine generation module **412**. As can be seen from these examples, the frequency of the sine wave generated by the sine/cosine generation module **412** is related to the value of N in the coefficient generation module **410**. Put another way, the frequency of the sine wave generated by the sine/cosine generation module **412** is $N$ times $f_0$, where $N$ is related to the number of iterations occurring in the coefficient generation module **410**.

Turning to FIG. **10**, what is shown is an alternative representation of the present invention incorporating both the coefficient generation module **410** and the sine/cosine generation module **412**. As shown in FIG. **10**, following the start **1010** of operation of the sine/cosine generator **400**, an initialization operation **1012** initializes variables for use by the coefficient generation module **410**. For example, the initialization operation **1012** preferably initializes A(N) to $\cos(2\pi N f_0 T)$; B(N) to $\sin(2\pi N f_0 T)$; C to $\cos(2\pi f_0 T)$; and D to $\sin(2\pi f_0 T)$. Next, a generation operation **1014** generates values for A(N) and B(N) in accordance with the operations previously discussed with respect to FIG. **7** and FIG. **8**. Sine/cosine determination operation **1016** then determines whether values representative of either a sine wave or a cosine wave are desired. If the sine/cosine determination operation **1016** determines that a sine wave is desired, set operation **1018** then sets y(0) = 0, and selects B(N) for input as $y(1)$ in the sine/cosine generation module **412**, and a sine wave is generated by generate sine wave operation **1020**. If the sine/cosine determination operation **1016** determines that a cosine wave is desired, set operation **1022** then sets y(1) = 0, and selects A(N) for input as $y(1)$ in the sine/cosine generation module **412**, and a cosine wave is generated by the cosine wave operation **1024**. After a sine or a cosine wave has been generated, next frequency determination operation **1026** determines if the next frequency of sine or cosine waves is desired. That is, the next frequency determination operation **1026** determines if the operational flow of the sine/cosine generator **400** should be continued such that another sine wave or cosine wave having a greater frequency should be generated. If the next frequency

determination operation **1026** determines that the next frequency sine or cosine wave is desired, the operational flow of the sine/cosine generator **400** is returned to the generate coefficients operation **1014** and the operational flow of the sine/cosine generator **400** continues on as shown in FIG. **10** until a next frequency is no longer desired.

In summary, in view of the foregoing discussion it will be understood that a first embodiment of the present invention provides a digital sine/cosine generator (such as **400**) having a coefficient generation module (such as **410**) which is operable to generate a series of values. The digital sine/cosine generator also includes a sine/cosine wave generation module (such as **412**) which is operable for receiving one of the values from the series of values generated by the coefficient generation module together with an initial value (such as **418** or **420**) indicative of a starting point of a periodic waveform. The sine/cosine wave generation module preferably employs the initial value and the value received from the coefficient generation module to generate a sequence of values representative of a periodic waveform.

With respect to the series of values generated by the coefficient generation module, preferably these values are generated either by an implementation of the equation $A(N) = \cos(2\pi NFT)$ (such as **734**) and/or by an implementation of the equation $B(N) = \sin(2\pi NFT)$ (such as **736**). Additionally, the series of values (such as **912**, **914**, and **916**) generated by the coefficient generation module is preferably representative of a sine wave, wherein the initial value is zero, and wherein the sequence of values generated by the sine/cosine wave generation module is representative of another sine wave (such as **920**, **922**, or **924**). The sine/cosine wave generation module of this first embodiment of the present invention preferably uses a discrete difference equation, such as $y(n) = b*y(n-1) - y(n-2)$, to generate the sequence of values representative of a periodic waveform, where $y(n)$ represents the output signals of the sine/cosine generator at discrete time n, and b represents a predetermined constant.

The coefficient generation module in this first embodiment of the present invention preferably comprises a digital sine/cosine wave oscillator (such as **410**) for generating N consecutive values of a sine wave. The coefficient generation preferably includes a first initializer (such as **812**), a calculator (such as **814**), an output (such as **816**), and a second initializer (such as **820**). The first initializer preferably sets a variable A equal to $\cos(2\pi FT)$, a variable B equal to $\sin(2\pi FT)$, a variable C equal to $\sin(2\pi FT)$, and a variable D equal to

$\cos(2\pi FT)$. The calculator accesses the variables A, B, C, and D and calculates a value $A(N) = AD + BC$, and a value $B(N) = AC - BD$. The output then outputs the values A(N) and B(N) and the second initializer sets the variable A equal to the value A(N) and the variable B equal to the value B(N) prior to the beginning of the next calculation by the calculator.

Preferably, the coefficient generation module simultaneously generates a first series of values representative of a sine wave (such as **736**) and a second series of values representative of a cosine wave (such as **734**). The digital sine/cosine generator also preferably also includes a selector module (such as **422**) selecting a value from either a first series of values representative of a sine wave or a second series of values representative of a cosine wave for receipt by the sine/cosine wave generation module.

Another embodiment of the present invention provides a computer-readable media having computer executable modules including a coefficient generation module (such as **410**) and a discrete periodic waveform generation module (such as **412**). The coefficient generation module preferably generates a first series of N consecutive values which may be characterized by the function $B(N) = \sin(2\pi NFT)$, wherein F is the base frequency of the function and T is the period between consecutive values. The discrete periodic waveform generation module preferably utilizes a difference equation to generate a sequence of consecutive values representative of discrete periodic waveform, using a predetermined value (such as **428**) as a first initial condition for the difference equation and one of the values of the first series of N consecutive values (such as **736**) as a second initial condition for the difference equation, such that frequency of the waveform generated by the discrete periodic waveform generation module has a frequency of N*F. Preferably, the difference equation in this embodiment of the present invention is characterized by $y(n) = b*y(n-1) - y(n-2)$, where y(n) represents the output signals of the periodic waveform generation module at discrete time n, and $b = 2\cos(2\pi FT)$.

The coefficient generation module in this embodiment preferably additionally generates a second series of N consecutive values (such as **734**) which may be characterized by the function $A(N) = \cos(2\pi NFT)$. This embodiment of the present invention also preferably includes a computer executable selector module (such as **422**) which is operable to select one of the values from either the first series of M consecutive values or the second series of N consecutive values as the second initial condition for the difference equation.

Yet another embodiment of the present invention involves a method of generating, using a discrete difference equation (such as **612**), a sequence of values representative of a periodic waveform (such as **430**). The method of this embodiment preferably includes the steps of comprising steps of selecting a first value representative of a first initial condition of the difference equation (such as **428**), generating a second value representative of a second initial condition of the difference equation (such as **410**), and calculating the sequence of values of the periodic waveform with the discrete difference equation using the first and the second values as initial conditions in the difference equation. The difference equation in this embodiment is preferably characterized by y(n) = b*y(n-1) - y(n-2), where y(n) represents the output signal of the sine/cosine generator at discrete time n, and b represents a constant.

The generating step in this embodiment of the invention preferably involves selecting one value from a series of values which may be characterized by the equation B(N) = sin(2πNFT), wherein F is the base frequency of the function and T is the period between consecutive values.

The generating step in this embodiment of the invention preferably comprises the steps of generating a first series of consecutive values (such as **418**) which may be characterized by the function B(N) = sin(2πNFT), generating a second series of consecutive values (such as **420**) which may be characterized by the function A(N) = cos(2πNFT), an selecting (such as **422**)as the second initial condition for the difference equation one of the values from the first series of consecutive values or one of the values from the second series of consecutive values.

Additionally, the generating step in this embodiment may comprise the steps of setting a variable A equal to cos(2πFT), setting a variable B equal to sin(2πFT) setting a variable C equal to sin(2πFT), and setting a variable D equal to cos(2πFT) (such as **812**). A value A(N) = AD + BC and a value B(N) = AC - BD are then calculated (such as **814**) and output (such as **816**). The variable A is then set equal to value of A(N) and the variable B is set equal to equal to the values of B(N) (such as **820**). These steps (such as **814**, **816**, and **820**) are then repeated a predetermined number of times. Finally, one of the outputted values is selected (such as **422**) as the generated second value representative of the second initial condition of the difference equation.

Another embodiment of the present invention relates to a digital sine/cosine wave generator (such as **812**) which includes a coefficient generator (such as **410**) for generating a series of values and a sine/cosine generation means (such as **412**) for receiving one of the series

of values and for generating a sequence of values representative of either a sine wave or a cosine wave using the received value as an initial condition of a difference equation (such as **612**).

It will be clear that the present invention is well adapted to attain the ends and advantages mentioned as well as those inherent therein. While a presently preferred embodiment has been described for purposes of this disclosure, various changes and modifications may be made which are well within the scope of the present invention. For example, the sine/cosine generator **400** may be employed in a system other than a disc drive device. Additionally, the sine/cosine generator **400** may be employed to generate a sine wave only or a cosine wave only. In such a case, the selector **422** shown and described with respect to FIG. **4** could be eliminated with the appropriate output of the coefficient generation module, either A(N) or B(N) going directly to the $y(1)$ input of the sine/cosine generation module **412**. Numerous other changes may be made which will readily suggest themselves to those skilled in the art and which are encompassed in the spirit of the invention disclosed and as defined in the appended claims.